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The abundance of nuclei heavier than oxygen in the primary cosmic radiation

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With 13 figures in the text

SUMMARY

Photometric measurements have been made on 61 tracks of heavy primary particles ($Z > 8$), which were found in an emulsion stack exposed over Texas at 41° geomagnetic latitude. The measurements have been corrected for different emulsion effects. The tracks were selected according to a track length criterion which states that the tracks to be accepted must be long enough to give a standard error in the determination of the charge not exceeding 0.30 units of charge. The charge calibration was made by δ-ray counting and by studies of break-up events. A small amount of fast but non-relativistic particles were found in the material. These particles have been identified from measurements of mean track width and rate of change of mean track width along the track.

The spectrum shows well-resolved peaks. The following observations are made in the spectrum. The ratio $N(17 \leqslant Z \leqslant 26)/N(9 \leqslant Z \leqslant 16) = 0.48 \pm 0.14$ at the top of the atmosphere. The abundance of odd nuclei is much less than the abundance of even nuclei. Neon, magnesium, and silicon are the most abundant elements and occur with approximately the same frequency. There are few primary particles in the charge region $17 \leqslant Z \leqslant 23$. There are two comparatively large particle groups, namely, chromium and iron of roughly the same size in the very heavy region. No particles heavier than iron have been found. The relative abundance of oxygen, silicon, and iron is discussed and compared with the mean universal abundance.

Introduction

The relative abundance of different elements in the primary cosmic radiation can certainly give some information about the chemical composition of the region where the particles originate and may thus also give information about the position of the cosmic ray source in the universe. We may also get some information about the history of the radiation starting with the time when by some acceleration process the particles reach an energy of a few MeV/nucleon, large enough for nuclear reactions to take place until they finally arrive at the outer boundary of our atmosphere. Accurate knowledge of the charge distribution of the primary radiation is thus of great importance for the development of a consistent theory of the origin and accelerating mechanism of the radiation.

Hitherto the major part of the experimental work on the identification of heavy primaries has been concentrated on the charge interval $3 \leqslant Z \leqslant 10$ with special attention to the abundance of Li, Be, B, relative to heavier elements [1–28]. This ratio gives information about the amount of interstellar matter which has been traversed and thus about the age of the radiation. In order to obtain information about the source composition and features in the accelerating mechanism it seems necessary to study in detail the relative abundance of all elements found in the radiation. There is reason to believe that important information can be obtained, especially from the heavy part of the spectrum ($Z \geqslant 10$). This part is however less well-known chiefly because of the considerable experimental difficulties which are associated with the attainment of an approximately complete resolution between consecutive charges [24, 29, 30, 31, 32].

Most studies of the heavy primary spectrum have been made with nuclear emulsions exposed in high altitude balloon flights. On account of incomplete resolution and of difficulties with the charge calibration the spectrum in most experiments has only been divided into 3 or 4 groups, and a comparison of the relative size of these groups has been performed. Difficulties with a correct and well-defined boundary between the groups have also made these figures slightly uncertain.

In a paper by Waldeskog and Mathiesen, which will be referred to as paper 1, these authors show that it is possible to get excellent resolution between consecutive charges in the region $3 \leqslant Z \leqslant 8$ by a photoelectric measuring technique in nuclear emulsions [33]. Their results show that it is reasonable to assume that almost the same resolution can be obtained also for particles heavier than oxygen, if the same technique is used.

The present paper describes a measurement of the heavier part of the primary spectrum ($Z \geqslant 9$) made with the same photometer as was used by Waldeskog and Mathiesen. The result of our work is a spectrum with a satisfactory resolution between the charges.

Exposure details

The balloon carrying the emulsion stack was launched in January 1955 from San Angelo, Texas, U.S.A. (41° geomagnetic latitude). The floating altitude was 29 km, and time of flight 8 hours. The time-altitude curve for the flight can be seen in paper 1.

The amount of matter above the emulsion stack was 14 g/cm^2 air + 1 g/cm^2 packing material for particles with vertical incidence. The mean value of the amount of matter through which the particles passed before reaching the stack was 18 g/cm^2. This figure takes into consideration the angular distribution of the particles.

Emulsion stack

The stack consisted of 40 Ilford G 5 emulsion sheets, each of 7.5×10 cm in size and 600 μ thick. It was flown with the emulsion surfaces vertical and with the small edge horizontal. The stack was enclosed in an airtight 1 mm thick aluminium container.

The emulsions were processed with an amidol developer according to the temperature development method. The degree of development is normal, the plateau value for singly-charged particles being 19 blobs/100 μ. The background of short electron tracks is fairly high.

Scanning

The scanning was performed according to a slightly modified line-scanning method. Each plate was scanned along 9 equidistant horizontal lines. The distance between the lines was 10 mm, and the first line was chosen 5 mm from the upper edge of the plate. With few exceptions every track will be found more than once. The scanning efficiency with this method is therefore practically 100 % for all charges.

All tracks accepted in the scanning must fulfil three conditions:

1. The charge must be $\geqslant 6$, which is concluded from observations of grain density, δ-ray density, and scattering.

2. The angle between the vertical line and the projection of the track into the emulsion plane must be $\leqslant 50°$.

3. The length of the projection of the track on to the emulsion plane must be $\geqslant 1.5$ mm.

The purpose of the investigation was to study the primary spectrum in the charge region $Z \geqslant 9$. Only tracks of particles whose charge was estimated to be at least equal to 8 were therefore accepted for measurement. The selection of the tracks to be measured was made by a very experienced scanner who had tracks of particles with known charge for the comparison. The accuracy of the estimate was checked repeatedly during the time of the investigation by comparisons between estimated charge and photometrically measured charge. We do not believe that any error in frequency of the lowest charges ($Z = 9, 10$) can have been caused by errors in the selection procedure.

All particles were traced backwards to the point where they entered the stack and forwards to the point where they interacted or left the stack.

The photometric instrument and the measurements

The photometer has earlier been described by von Friesen and Kristiansson [34], the electronics and the registering system by von Friesen and Stigmark [35]. The instrument is principally unchanged, but we have had to choose a wider slit more suitable to measurements of tracks of multiply-charged particles. The dimensions of the new slit are 3 mm × 0.25 mm, which is equal to $54\,\mu \times 4.5\,\mu$ in the object plane. The objective is a Leitz, Ks 53 ×.

The measuring technique is essentially the same as has been described in earlier papers about the method. The mean track width (MTW) in a 54 μ long section of a track is determined by three readings, the first one with the slit covering the track, and the second and third ones with empty slit. The difference between the mean value of the "background" readings and the reading with the track in the slit determines the area of the track. In measurements on thick tracks we found it advantageous to measure the background above and below the track. This change in the measuring technique is discussed in paper 1.

The speed of the measurements is comparatively high, about 12 mm/hour, for a straight, horizontal track. For strongly dipping tracks ($\simeq$ 1.5 mm/pellicle) the speed is reduced to about 6 mm/hour depending on larger difficulties in the adjustment of the track in the slit and frequent plate changes.

We have measured $\frac{2}{3}$ of the length of the track in each plate. About $\frac{1}{6}$ of the track length has been left out near the surface and the same length near the glass. The reason for this exclusion is to avoid such parts of the emulsions in which disturbances from the handling of the pellicles may appear. When, in the discussion below, the track length is given, it indicates the total projected length of the track whereas the distance which has been measured is $\frac{2}{3}$ of it.

The reproducibility of the instrument has been tested by repeated measurements on a track of an oxygen nucleus. The results are shown in Table 1. The figures are properly corrected according to the discussion in the following chapters. The reproducibility of the instrument seems to be good. The small variations which still exist do not give rise to errors large enough to have any influence on the particle identification.

Table 1.

Date of measurement	Mean track width (arbitrary units)
2 Dec. 1958	100.9
30 Jan. 1959	99.6
27 Feb. 1959	100.0
8 April 1959	100.3
16 April 1959	99.3

Depth correction

It has always proved necessary to apply a correction on the MTW values for disturbing emulsion effects such as light scattering and variations in the degree of development [36]. The corrections depend on the depth in the emulsion at which the measurement takes place and are brought about by applying correction factors which reduce all readings to the same level in the emulsion. The size of this correction on tracks of multiply-charged particles is discussed in paper 1 and will not be repeated here.

In paper 1 the influence of the mean width of the tracks on the correction was studied by a comparison of correction factors for tracks of different charges ($4 \leqslant Z \leqslant 12$). The charge interval was, however, too small to give a significant result but a small increase of the correction was noticed when MTW increased. In the present work the investigation has been extended to $Z = 26$, and the increase has been confirmed. In spite of this, we have found that two sets of correction factors are sufficient, one for MTW values corresponding to the charge interval $8 \leqslant Z \leqslant 16$, and one for the interval $16 < Z \leqslant 26$.

Unfortunately, we had to process the stack in parts with as a rule 6 pellicles in each part. In spite of great care and as accurate repetitions of the processing as possible there are some differences in the degree of development and still more in the transparency. We have therefore had to use different sets of correction factors for different batches.

Dip correction

The influence of the dip angle on the results of mean track width measurements has been studied in previous papers. It has been found that no corrections were necessary for singly-charged particles with as high a dip angle in unprocessed emulsion as $\alpha = \arctan 0.4$, if appropriate dimensions were chosen for the slit [37]. From paper 1, it is also evident that for multiply-charged particles no correction is necessary as soon as $\alpha \leqslant \arctan 0.2$.

In the present study we have increased the angular interval for the acceptance of a track to $\alpha = \arctan 0.45$ in order to get better statistics. Because of the increase in the dip angle and the great difference in MTW between tracks of oxygen and iron nuclei, it has been found technically impossible to choose such slit dimensions that dip corrections vanish for all angles and all charges. The dimensions have however been chosen in such a way as to get as small corrections as possible.

The dip correction factors depend chiefly on three effects which will be discussed.

1. The measurements take place with a slit with constant length; this means that the real length of a section of the track covered by the slit varies as the function $\sqrt{1+\tan^2\alpha}$ where α is the dip angle in the unprocessed emulsion. The number of grains in a slit length changes in the same way but the mean track width as determined by the photometer may not necessarily increase with α to the same extent due to changes in the overlapping of the grains. For a thin track with completely separated grains the increase in MTW will follow the function $\sqrt{1+\tan^2\alpha}$, if other effects are excluded. For a wide and completely dense track without any δ-rays, which can be well approximated by a cylinder, the projection has practically the same width as the track itself, and the mean track width will be independent of the dip angle. A track of a multiply-charged particle can be considered with some approximation as built up of a tight cylinder and completely separated grains. The relative size of the two parts depends on the charge of the particle. It is therefore to be expected that the projected area of the track, $P(\alpha)$, seen by the photo-tube, can be written

$$P(\alpha) = P(0)\cdot(a + b\sqrt{1+\tan^2\alpha})$$

$$a + b = 1,\ a \text{ and } b \geqslant 0$$

where a and b are constants for tracks of given width, a representing the solid cylindrical part of the track and b the free grains.

2. When dipping tracks are measured the track is focused sharply in the middle of the slit with both ends of the track defocused. A correctly adjusted instrument gives smaller MTW for a defocused track than for a track sharply adjusted in the slit. This means that a dipping track, part of which must be defocused, has less MTW than a horizontal track with the same number of grains per slit length. An estimate of the loss of MTW as a function of the defocusing has been obtained from repeated MTW readings on the same section of a horizontal track gradually defocused. The percentage loss in MTW for a dipping track is then calculated by a proper integration over the whole slit length of the loss in MTW obtained in the defocusing measurements. The results are shown in Figure 1. The loss is as high as about 9 % for the maximum dip angle accepted. It is not very sensitive to the mean width of the tracks.

3. The third effect is a microscope effect which depends on the adjustment of the instrument. We have found that the maximum reading is not obtained when the

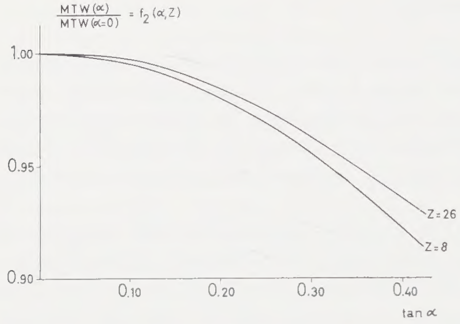

Fig. 1.

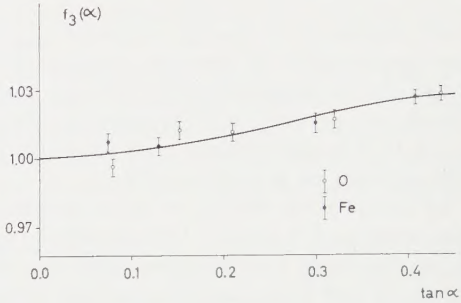

Fig. 2.

Fig. 1. The mean track width as a function of the tangent of the dip angle, α, when measurements are made on tracks, whose areas, projected on the slit plane, are the same.

Fig. 2. The influence of the microscope factor, $f_3(\alpha)$, on the MTW reading as a function of the dip angle of the track. The factor has been normalized to 1.00 for $\alpha = 0$. It has been determined both on oxygen and iron tracks and does not show any dependence on the mean track width.

image of the track is sharply adjusted in the slit but when it is slightly defocused. As a measurement takes place when the track is sharply focused the result of the measurement will be a MTW value which is less than the maximum value. Figure 2 shows the effect and how it depends on dip angle. The loss in MTW has been determined from two measurements on each section of the track, the first one with the track in normal measuring position and the second one with the track in a position to give maximum MTW.

The conclusion of the discussion about the influence of dip on the MTW measurements leads to an assumption that with fairly good approximation

$$\mathrm{MTW}\,(\alpha) = \mathrm{MTW}\,(0) \cdot \left(a + b\sqrt{1 + \tan^2\alpha}\right) \cdot f_2(\alpha, Z) \cdot f_3(\alpha)$$

where

MTW (α) = the mean track width for a track with the dip angle = α

MTW (0) = the mean track width when the dip corrections are applied

a and b = constants, earlier discussed

$f_2(\alpha, Z)$ and $f_3(\alpha)$ = functions depending on dip angle and charge and shown in Figures 1 and 2.

Figure 3 shows MTW(α) as a function of tan α for oxygen, silicon, and chromium nuclei. To give some idea of the distribution of the measurements around the calculated curves, we have also plotted the MTW values for the particles which have been identified as oxygen, silicon, and chromium nuclei. The values of MTW(0) and the constant a in the formula have been adjusted to give the best agreement between the curves and the measurements. Figure 4 shows the values which have been used for the constant a and which seem to be quite reasonable if the meaning of the constant is taken into consideration. The agreement between curves and measure-

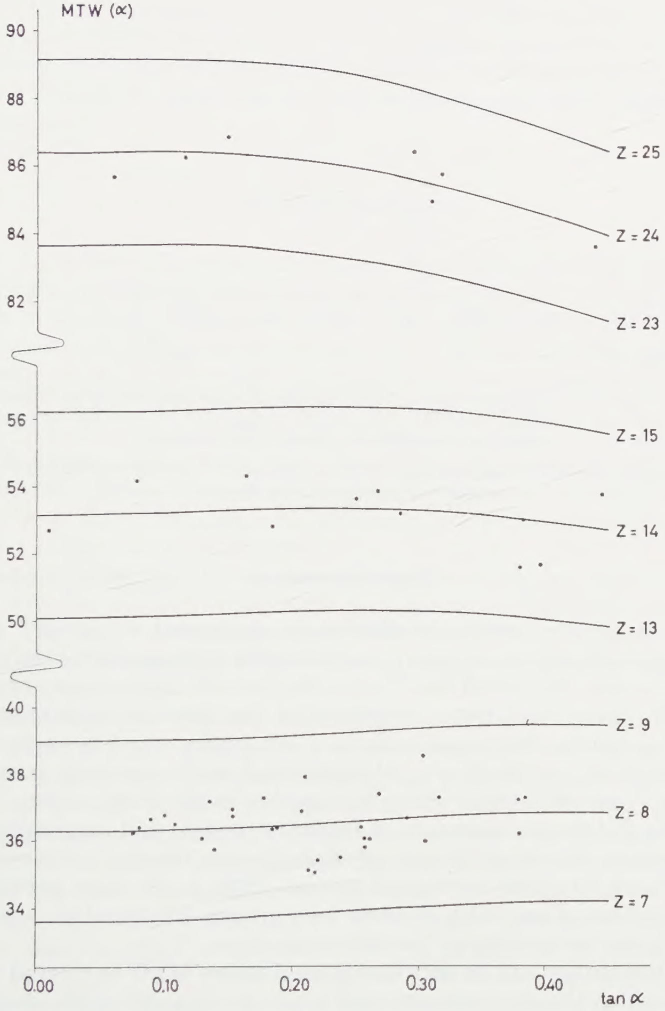

Fig. 3. Computed relations between MTW (α) and tan α for oxygen, silicon, and chromium nuclei and experimental MTW values from measurements of particles assumed to belong to one of these kinds of particle. The MTW values are given in arbitrary units.

ments is satisfactory both for the three charges in Figure 3 and for other charges where the number of particles is great enough for a check.

The conclusion which can be drawn from the discussion on the influence of dip is that it is possible to measure tracks with large dip angle and to identify the particles with the same accuracy as particles passing through the pellicles with small dip angles. Without losing in accuracy, it is therefore possible to extend the allowed dip angle to $\alpha = \arctan 0.45$ and in this way to increase the statistics appreciably.

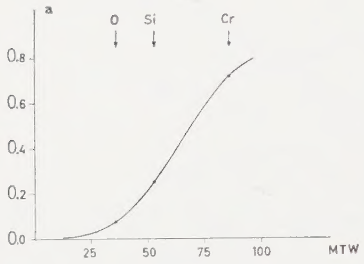

Fig. 4.

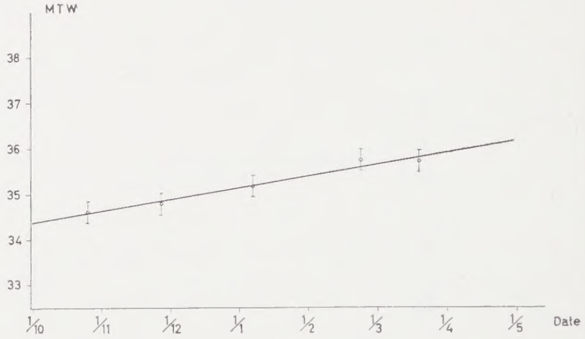

Fig. 5.

Fig. 4. The fraction (a) of the track area, which forms the core as defined in the dip correction discussion, plotted as a function of MTW. The MTW values for relativistic oxygen, silicon, and chromium nuclei are indicated by arrows.

Fig. 5. The variation of MTW with the time of measurement. Each point includes measurements of ten particles in the mean.

Time correction

The period of the photometric measurement amounted to about 7 months. The speed of the measurement was roughly constant with approximately the same number of tracks each month. We found that during the time of measurement the MTW readings increased slightly and that a correction for this time dependence was necessary. The observation of the effect was made in a few tracks which were measured more than once. One track was used as a reference track and repeatedly measured, and a few others were measured twice owing to mistakes in the bookkeeping. The increase was also visible in the measurements of tracks of oxygen and magnesium nuclei. An early measurement of a track in one of these groups resulted as a rule in a lower MTW value than a late measurement of another track in the same group. On account of the large number of particles in these two groups we found it most convenient to use them in the calculation of the time correction.

The size of the change can be seen in Figure 5 where MTW is plotted as a function of the date at which the measurement took place. Each point in the diagram includes about 10 tracks of oxygen and magnesium nuclei. The magnesium MTW values are reduced by a proper factor to the oxygen MTW level before the mean values are taken. The increase in MTW amounts to about 0.7 % per month.

On account of the poor statistics it has not been possible to observe if the time correction also depends on the MTW of the track. It cannot be excluded, however, that a small dependence of this kind exists. Such a variation will have the greatest influence on the identification of the heaviest particles where the percentage difference between consecutive charges is least. To reduce the influence of possible effect of this kind all tracks of particles with $Z > 16$ have been remeasured in succession in the last three weeks of the period of measurement.

The variation of MTW with time seems to be due to an ageing effect of the microscope lamp. During the course of the measurement a black deposit precipitated on the glass bulb. This deposit scatters the light and a shift in the spectral composition takes place towards the red. Red light is scattered less than blue light in the emulsion and a photometric MTW measurement gives a higher mean width for a track when measured in red light than in blue. When unfiltered light is used it is therefore to be expected that the MTW values will increase when the lamp ages just as was found in our measurements.

Plate normalization

The stack is processed in groups containing 6 or 4 pellicles in each batch. We have tried to perform the different processings as similarly as possible, but in spite of that it is possible to observe differences both in the transparency and in the degree of development between different batches and also between different plates in the same batch. In order to be able to make comparisons between measurements in different plates all MTW values have therefore got to be normalized.

The most common way to determine normalizing factors is to measure the density of tracks of the same kind in each plate. The factors are inversely proportional to the measured density. The number of heavy primary particles with well-defined charge and velocity is however too small in our stack to give satisfactory accuracy in the determination of the factors in this way.

Another appropriate way to determine the plate factors in photometric measurements is to measure tracks of relativistic particles which have traversed all pellicles in the stack. The number of tracks which fulfil the above-mentioned conditions and which also have a satisfactory length in each pellicle is however too small to get sufficient accuracy.

A third possibility is to determine normalizing factors between adjacent pellicles through the whole stack and to get the definite factors by successive multiplication of the relative factors. The factor normalizing two adjacent plates can be determined accurately because the number of measurable tracks passing two plates is large. When the factors are multiplied the errors will be added, which means that the error in the factors will be larger the larger the distance is between the two pellicles to be compared. In our case it is possible to determine the factor between two adjacent plates with an error of about 0.5 %. In all we have used 36 pellicles in our stack which means that the error in the factor will be about 3 % when measurements in the first and in the last plate are compared. Such an error is too large to be accepted. The reason is that the difference in MTW between tracks of two consecutive charges is only about 4 % for particles in the region $20 \leqslant Z \leqslant 26$.

We have calculated the normalizing factors in two different ways. In the first calculation we have chosen a mean course between the last two methods. We have selected tracks which pass through all pellicles in two adjacent development batches and from them we have determined the relative factors of normalization between the batches. The definitive batch factors are then obtained by successive multiplication of the relative factors. The number of tracks traversing all pellicles in two adjacent batches is large enough to give small errors in the relative factors. The number of bachtes is furthermore small enough to give a satisfactorily small error also in the factor between the first and last batch of the stack.

In the second calculation the normalizing factors were determined by comparing the MTW of the same kind of track which are found in different parts of the stack. Such comparisons have been made with tracks of oxygen and magnesium nuclei.

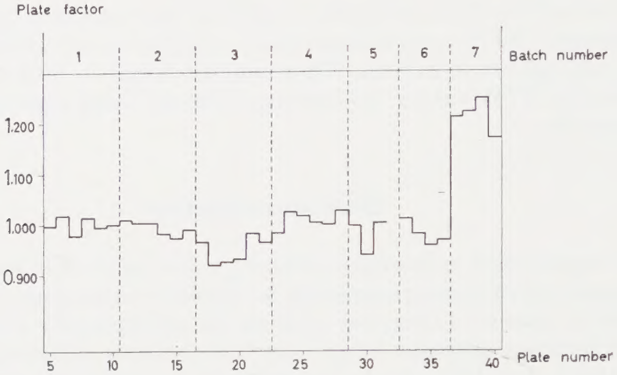

Fig. 6. Plate normalization factors.

The factors are in agreement with the results of the first calculation, but the errors are slightly larger. The definite batch factors can be seen in Table 2. They are weighted mean values of the two methods of determination.

Table 2.

Batch No.	Normalizing factor
1	1.000
2	0.993 ± 0.005
3	0.947 ± 0.006
4	1.008 ± 0.007
5	0.981 ± 0.008
6	0.982 ± 0.008
7	1.215 ± 0.009

The normalization factors for the plates in each batch are determined from measurements on tracks passing through the whole batch. They are shown in Figure 6.

Some remarks concerning the figure has to be made. Plates nos. 1–4 have been excluded because of disturbances from X-ray marks intended for the orientation of the pellicles. Plate no. 32 has been excluded on account of exceptionally large irregularities in the mean level of MTW in different parts of the plate. Plates nos. 36–40 show low values of MTW with correspondingly high normalization factors. This seems to be due to very large light scattering in the emulsions depending on too short a fixation time. On account of the large factors, we have checked the reliability of the measurements. We found that a measurement in this batch is as good as in the other batches and that there was no reason to exclude it from the stack.

Criteria of track acceptance

All tracks which are measured and included in the statistics have fulfilled the following five criteria.

1. The track must be produced by a particle entering the stack from the upper

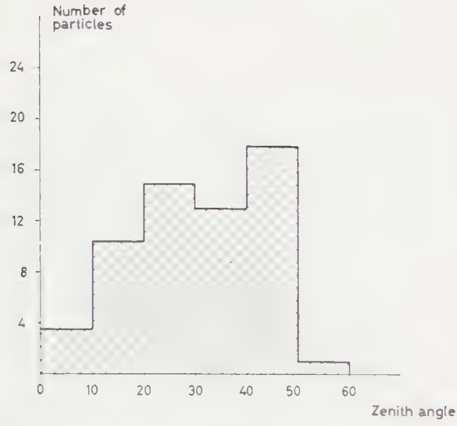

Fig. 7.

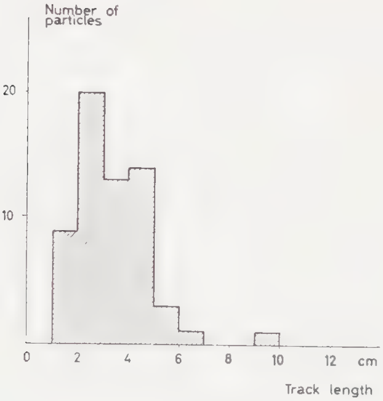

Fig. 8.

Fig. 7. The zenith angle distribution of the particles accepted for measurement.
Fig. 8. The track length distribution of the particles accepted for measurement.

hemisphere. The fact that the track is made by a particle entering from outside has been checked by following the track backwards to the point of entry in the stack.

2. The angle between the projection of the track into the emulsion plane and that edge of the emulsion which has been vertical during the balloon flight is not allowed to exceed 50°. With good approximation this angle is the same as the angle between the projection and the vertical direction. That this is the case is found from a study of the angular distribution of a large number of tracks in the stack.

3. The angle between the track and the emulsion plane must fulfil the condition $\tan \alpha \leqslant 0.45$ where α is the dip angle in the unprocessed emulsion.

4. No measurements are made on a track at a distance less than 10 mm from the edge of the emulsion. This condition eliminates errors in MTW caused by edge effects.

5. The total length of a track accepted for measurement must exceed a minimum length which is determined in such a way that the error in the charge determination caused by the error in MTW must be below some given value. This criterion is discussed in the next chapter.

In all, 61 tracks of heavy primaries with the charge $Z > 8$ fulfil the above-mentioned criteria and have been measured. Their angular distribution is shown in Figure 7. The track length distribution is shown in Figure 8.

We have furthermore measured 32 tracks of oxygen nuclei. They are used as the starting point for the charge scale and from the distribution of the measured charges in this fairly large group important information has been obtained about the sources of error in the charge determinations.

The track length criterion

In most investigations of the heavy primary particles in the cosmic radiation the limits of acceptance of a track have been fixed by comparatively simple geometrical conditions to make the stereo angle easy to calculate. Such measurements which

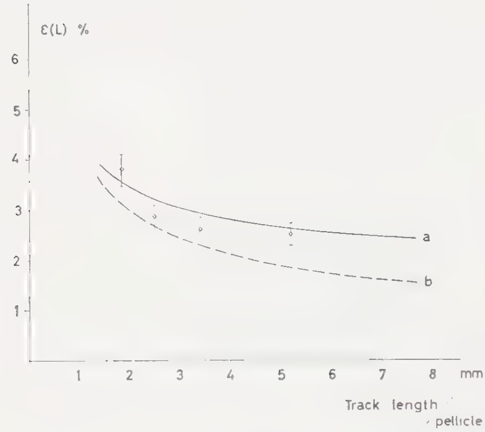

Fig. 9. The percentage standard error in the measurements of MTW in one plate as a function of track length per plate. The experimental results, which have been plotted together with two curves, are obtained from measurements on tracks of oxygen and neon. For curve *a* it is assumed that the error is composed of two parts, the first part is inversely proportional to the square root of the track length per plate, and the second one is independent of the track length. In curve *b* only an error of the first type is taken into consideration.

give the intensity of the radiation are made with greater statistical accuracy than what is possible in our comparatively small stack. The main object of our work is to obtain as complete a resolution as possible between consecutive charges in order to be able to study the fine structure of the particle spectrum. One of our criteria for the acceptance of a track is therefore that the measurements shall give the charge with an error from the MTW measurements not exceeding a value determined by the requirements of charge resolution. The criterion is found to be a track length criterion. It states that a track length is required such that the resolution in the charge spectrum is not lost on account of too large a statistical error in the MTW due to too short a track length or to too few measurements.

The error in the MTW value of a track is determined by the width of the distribution of the individual MTW readings and the number of such readings which can be obtained on the track. As a good approximation it could be expected that the error in MTW should be equal to $\sigma/\sqrt{n}$, where σ is the standard deviation of the individual readings and n the total number of such readings. Experimentally, we have however found that the error is larger and depends in a more complicated way on the number of readings.

The error in MTW in measurements in one pellicle on a track of the length L for each pellicle can be written

$$\varepsilon(L) = \sqrt{\left(\frac{\sigma_0}{\sqrt{n}}\right)^2 + \varepsilon_0^2}$$

where n is the number of readings and σ_0 and ε_0 are constants. The formula shows that the error $\varepsilon(L)$ can be regarded as composed of two parts, one part, $\sigma_0/\sqrt{n}$, which depends on the track length and another part, ε_0, which is put constant and independent of L. The main source of the error ε_0 is extended irregularities in the emulsion. There is reason to believe that ε_0 diminishes when the track length for each pellicle increases, but the reduction is so slow that it can well be approximated by a constant for the actual track lengths.

Figure 9 shows $\varepsilon(L)$ as a function of track length for each pellicle. Curve a is cal-

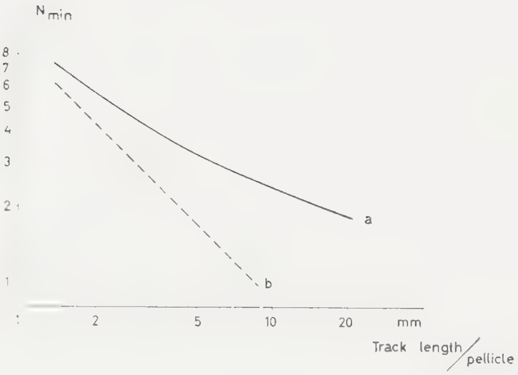

Fig. 10. The track length criterion for the acceptance of a particle. Curve *a* shows the least number of plates in which a track must be measured as a function of track length per plate. Curve *b* shows the corresponding numbers calculated on the assumption that no extended irregularities exist in the emulsion.

culated for oxygen tracks with the above-mentioned formula and with $\sigma_0 = 14.8\,\%$ and $\varepsilon_0 = 1.9\,\%$. The constants are obtained from a study of the distribution of the MTW readings in oxygen tracks.

The four points which are plotted in Figure 9 are experimental values. They are determined from the distribution of the individual plate values of MTW of tracks passing through several plates. Each point is a mean value of $\varepsilon(L)$ of about ten tracks, most of which are made by oxygen but a few neon tracks are included in the material to increase the statistics. The measurements seem to be in at least approximate agreement with curve *a*. Curve *b* is calculated on the assumption that the error simply varies as $n^{-1/2}$. The difference between the two curves is appreciable especially for flat tracks with long track length for each pellicle.

The total error in MTW when the track is measured in N pellicles is equal to

$$\varepsilon(N) = \varepsilon(L) \cdot N^{-1/2}.$$

As has been pointed out earlier, one of our criteria for the acceptance of a track is that the standard error in the charge determination caused by the error in MTW must be small enough to give satisfactory resolution between consecutive charges. We have decided to put this upper limit of the error to 0.2 units of charge for oxygen nuclei. This criterion together with the resolving power of the photometric method, $\partial \mathrm{MTW}/\partial Z$, determines the least number of plates, $N(L)_{\min}$, in which a track of given length per emulsion must be measured. $N(L)_{\min}$ is calculated from a formula

$$\frac{\varepsilon(L)}{\sqrt{N(L)_{\min}}} = \frac{100}{\mathrm{MTW}} \cdot \frac{\partial \mathrm{MTW}}{\partial Z} \cdot \Delta Z.$$

Figure 10 shows the calculated minimum number of plates as a function of track length per emulsion.

If a comparison between the relative abundance of different charges is to be made, the same geometrical criterion of acceptance must be chosen for all particles irrespectively of the charge. That means that if the criterion in Figure 10 is used for all kinds of particles the standard error in the charge will vary with the charge depending on variations in $\varepsilon(L)$ and in $\partial \mathrm{MTW}/\partial Z$. The least favourable resolution between two consecutive charges is found in the iron region, where the error in the charge from the MTW readings is about 0.30 units. This error is however small enough to give quite satisfactory results.

It must be pointed out that the criterion stated in Figure 10, curve a, is a criterion for the minimum number of plates. Whenever a track passes through additional plates, it has been measured in as many plates as possible.

Charge calibration

At that geomagnetic latitude where the plate exposure took place and at the top of the atmosphere all primary nuclei can be expected to be relativistic or nearly relativistic, e.g., they can be correctly identified from measurements of their ionization only. At the depth of the balloon flight a small fraction of the particles may have lost energy to such a degree that they fall outside the relativistic region and have to be identified from the measurements of two parameters. This section of our paper will discuss the relation between the particle charge and the mean track width for relativistic particles; and the next section will be confined to the identification of the non-relativistic particles.

The measurement of the MTW of a track is only relative, and it does not give any information about the absolute number of elementary charges carried by the particle producing the track. Accordingly, some kind of calibration is necessary. For relativistic particles we have used two methods, δ-ray counting and a study of such nuclear interactions between the cosmic ray particles and the emulsion nuclei which give rise to typical break-up events.

The δ-ray method.—This method has been used for calibration purposes in most investigations of the heavy cosmic ray spectrum. The reason is the simple relation between the δ-ray density, n_δ, and the charge valid for relativistic particles,

$$n_\delta = a\,Z^2 + b$$

where a and b are constants which must be determined experimentally from measurements on tracks of particles with known charge. Protons and α-particles, which are easily identified by other methods, are sometimes used for the calibration. As the δ-ray density is fairly low in such tracks, it is very difficult to reach satisfactory accuracy in the constants. Another disadvantage is the position of the two calibration points at one end of the charge scale. Better results are as a rule obtained if additional particles with the charge $6 \leqslant Z \leqslant 10$ can be identified and used. In this case the correctness of the charge calibration depends on the identification of these particles.

In our calibration by δ-ray counting we have made use of a study of the charge spectrum in the interval $Z \leqslant 10$ in the same plates (paper 1). In this work photometric MTW measurements divided the particles into groups which were resolved from each other. It was assumed that each group contained only one kind of particle and that adjacent groups contained particles whose charge differed by one unit. δ-ray counting was made on tracks in each group. As the number of tracks in the different groups was large, the δ-ray density could be determined with such accuracy that the results of the δ-ray counting gave a single-valued answer to the question about the absolute number of elementary charges of the particles in the different groups (paper 1 and [38]).

In the beginning of our measurement of the heavy part of the particle spectrum, we remeasured some of the particles which were identified in the earlier investigation. In this way we obtained a secure fixing of the low end point of the charge scale.

Owing to the extremely favourable combination of the two identification methods, we are confident that this fixing is correct. Because the δ-ray counting method is not suitable to particles with the charge $Z > 10$, we did not use it for heavier particles.

Nuclear interactions.—For charges with $Z > 10$ the calibration has been performed by the use of interactions between the cosmic ray particles and the emulsion nuclei. Only what is called break-up events can be used and also these events must be chosen with great caution. One type of break-up events which can be accepted shows neither evaporation tracks nor grey tracks. Such an event can be a collision between the particle and a free proton. If no charged mesons are produced the charge of the cosmic ray particle will be equal to the total charge of the outgoing particles minus the charge of the knocked proton. A collision with a neutron on the periphery of a nucleus can however give rise to the same type of event, but in this case the charge of the particle is equal to the total charge of the outgoing particles. We have found no satisfactory interaction of this type in our material. We have therefore chosen collisions between particles and nuclei in which the collision products can be distinctly divided into two groups, one shower containing the primary particle fragments, and one group of evaporation particles from the target nucleus. Only such events are chosen which show a small visible excitation energy in the target nucleus. Under such circumstances the probability is small for a charged particle from the target to fall into the shower and be accepted as a fragment. Also in this case it must be kept in mind, however, that a collision can take place with a peripheral proton and that this proton can receive large energy and fall in the shower. In this case the counting of the number of charges in the shower gives a charge one unit too high. The production of charged π-mesons can furthermore give rise to serious mistakes in the calibration.

In Table 3 those break-up events are collected which seem to be most suitable for calibration purposes. They all show a rather narrow opening angle for the shower, and the visible energy in the grey and black tracks is low. In two columns of the table the component of the momentum in the direction of the primary particle both for the singly-charged fragments and the evaporation particles is given. The figures show that the particles can be divided into two distinct groups.

Calibration procedure.—The charges 8 and 10 are identified as described in the section about the δ-ray counting and plotted in a MTW charge diagram; and we can by extrapolation predict an approximate MTW value for charge 12. A support of the extrapolation is event number 1 in Table 3. A large and well-defined group of tracks, whose MTW corresponds to $Z = 12$, are found among the measured particles. The mean value gives a better MTW for $Z = 12$. A similar extrapolation procedure with the support of reaction 2 puts Si on the MTW scale. A third extrapolation gives the position of sulfur accurately, and argon with a somewhat larger error. The events numbers 3, 4, and 5 determine the charge calibration in the iron region. Among them event no. 3 gives the most important contribution. If it is assumed that argon is correctly identified the primary particle in this event must be either chromium ($Z = 24$) or vanadium ($Z = 23$), depending upon whether the singly-charged particle is a proton or a meson. It thus allows of an uncertainty of only one unit of charge in the region. A very strong support for the correctness of the identification made in the table is the following fact. If we assume the primary particles in the events 3 and 4 to be chromium, the group with the highest charge in the spectrum will be identified as iron. If the particles are vanadium, the maximum charge will be $Z = 25$ (manganese). But the relative abundance of iron in the universe is much higher than

Table 3. Energy and momentum are calculated on the assumption that all singly-charged particles are protons.

Event no.	Primary nucleus	Fragmentation products	Measured charge of the primary particle	Measured charge of the heavy secondary particle	Root mean square opening angle of the light fragments	Longitudinal momentum of the singly-charged fragmentation products (GeV/c per nucleon)	Number of grey or black tracks	Visible energy in the grey or black tracks (MeV)	Longitudinal momentum of singly-charged particles making grey or black tracks (GeV/c per nucleon)
1	Mg	Ne + 2 p	12.2	10.2	4.9°	$p_1 \simeq 1.55$ $p_2 \simeq 1.30$	1	25	$p_3 = +0.087$
2	Si	4 α + 6 p	13.9	—	2.4°	$p_1 \simeq 2.0$ $p_2 \simeq 2.4$ $p_3 \simeq 2.4$ $p_4 \simeq 2.4$ $p_5 \simeq 2.4$ $p_6 \simeq 2.4$	3	129	$p_7 = +0.426$ $p_8 = +0.004$ $p_9 = -0.044$
3	Cr	A + Li + α + p	24.1	17.8	1.3°	$p_1 \simeq 1.7$	2	6	$p_2 = -0.037$ $p_3 = +0.071$
4	Cr	S + 8 p	23.8	16.2	13.2°	$p_1 \simeq 0.62$ $p_2 \simeq 1.5$ $p_3 \simeq 1.7$ $p_4 \simeq 1.3$ $p_5 \simeq 1.5$ $p_6 \simeq 1.2$ $p_7 \simeq 0.82$ $p_8 \simeq 0.73$	3	$\simeq 400$	$p_9 \simeq +0.300$ $p_{10} = \pm 0.000$ $p_{11} = -0.035$
5	Fe	Ti + α + 2 p	26.3	22.2	0.3°	$p_1 > 10$ $p_2 > 10$	4	9	$p_3 = +0.047$ $p_4 = -0.057$ $p_5 = +0.038$ $p_6 = +0.042$

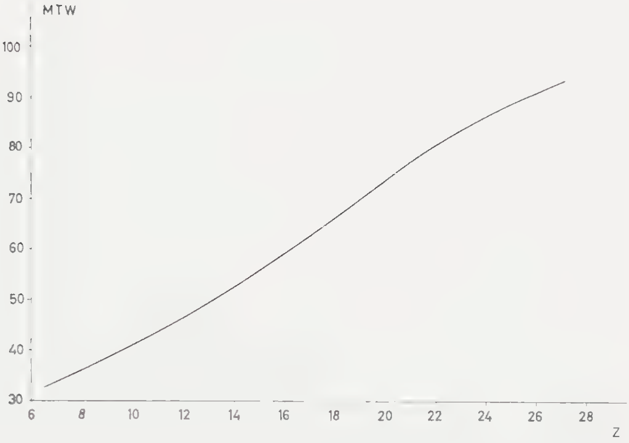

Fig. 11. The MTW–charge relation for relativistic particles.

the abundance of manganese, and there is therefore no reason to assume that the group with the highest charge does not represent the iron nuclei but manganese of unaccountable origin.

The conclusion from the discussion is that it has been possible to calibrate the whole charge region $8 \leqslant Z \leqslant 26$, and we believe that the possibility of our having made errors in the charge scale is small.

Figure 11 shows the calibration relation between MTW and charge in the interval $8 \leqslant Z \leqslant 26$. The analogous calibration curve for charges less than eight was published in paper 1.

The abundance of non-relativistic particles in the spectrum

In a spectrum of heavy primary particles at 41° geomagnetic latitude and at a depth in the atmosphere of about 15 g/cm^2, it can be expected that there is a non-negligible number of primary particles which are fast but not relativistic. These particles will be wrongly identified if they are assumed to be relativistic, and if their charge is determined from the measurement of only one parameter, the ionization. Non-relativistic particles can be expected to appear, especially at large zenith angles, owing to both the east — west asymmetry and the passage through a large amount of matter.

A fast but not relativistic multiply-charged particle is usually identified from measurements of ionization and small angle scattering. An accurate and correct determination of the mean scattering angle can be obtained only when the track length for each pellicle is appreciable, because only in this case the influence of the distorsion of the emulsion on the scattering angle is reduced to a harmless level.

A track which is suitable for measurements of small angle scattering having a long track length for each pellicle, as a rule passes through few pellicles. In a previous section of this paper it has been shown that the most accurate measurement of the ionization is obtained for a particle which passes through a large number of plates. Local irregularities in the emulsion are eliminated in this case much quicker than if the whole measurement takes place in one plate only. That means that the tracks in which the most accurate ionization measurements can be made are unsuitable for small angle scattering measurements.

On account of these difficulties we have tried to identify particles by combining measurements of MTW and rate of change of MTW along the track. In principle this method is always possible to use for charge identification but in practice it is often difficult to determine the rate of change of MTW with satisfactory accuracy. Thus we have found that the lower track length limit for the applicability of the method is about 25 mm. Furthermore, it has proved necessary to reduce the influence of local irregularities in the pellicles by requiring that the track be measured in at least 6 plates. If a track fulfils these geometrical conditions, identification is possible as soon as the particle momentum is less than some value, $p_1(Z)$, which, as an example, is equal to 1.2 GeV/c per nucleon for magnesium and 1.5 GeV/c per nucleon for iron. The method is discussed in a special paper to which the reader is referred for details [39].

We have in all measured 32 oxygen tracks and 61 tracks of particles with $Z > 8$. Of these 65 tracks fulfil the conditions stated for the new identification method, and their rate of change of MTW, ΔMTW/ΔR, is calculated. Ten particles show a value which is definitely larger than 0. We have assumed that these particles are non-relativistic and possible to identify from MTW and ΔMTW/ΔR. Relations between MTW, ΔMTW/ΔR, and Z are calculated and shown in a figure in the above-mentioned paper [39]. The results of the charge determinations of the non-relativistic particles are also shown in Table 4. In the last column a set of incorrect Z values are given. They are obtained on the assumption that all particles in our material were relativistic and could be identified merely from their MTW and the charge calibration curve in Figure 11. Errors of several units of charge arise and particles heavier than iron can wrongly be assumed to exist in comparatively great numbers.

Table 4.

Particle number	MTV arbitrary units	Δ MTW/ΔR units/cm	Z	Z (wrong)
233–18	48.7	1.80 ± 0.42	9.6	12.7
225–24	45.5	0.68 ± 0.38	9.9	11.6
236–57	64.7	2.95 ± 1.00	14.0	17.5
218–30	58.4	0.66 ± 0.18	14.2	15.7
217–59	73.0	1.16 ± 0.24	17.7	19.6
216–57	80.1	1.84 ± 0.18	18.9	21.6
223–25	80.7	0.76 ± 0.14	20.3	21.8
206–33	90.6	0.71 ± 0.40	23.8	25.5
214–80	93.8	1.48 ± 0.16	23.8	27.0
208–52	98.1	1.02 ± 0.14	26.3	29.0

The occurrence of 10 non-relativistic particles among the 65 particles measured shows that a fairly large fraction of the primary particles is non-relativistic at balloon flight altitude. In Table 5 the particle spectrum has been divided into three groups and in each group the number of non-relativistic particles is given and compared with the total number of particles in the same group. It must be pointed out that the number of particles in the oxygen group should not be compared with the number of particles in the other two groups because the oxygen group is used only for calibration purposes and does not include all oxygen tracks in the stack.

Table 5.

Charge	8	9–16	17–26
Number of non-relativistic particles	0	4	6
Number of particles whose Δ MTW/ΔR can be determined	23	31	11
Total number of particles measured in the stack	32	45	16

The figures in the table show that the relative number of non-relativistic particles increases with increasing charge. The explanation seems to be the following. From the oxygen group in the Table 5 it can be concluded that at the top of the atmosphere all particles have a relativistic energy, i.e., all particles can be identified from measurements of only one parameter. the ionization. In the passage through the atmosphere to the emulsion stack energy is lost. The energy loss per nucleon is proportional to the charge and thus largest for particles in the last column in the table. The energy loss, which also depends on the balloon flight altitude and the zenith angle of the particle, is precisely large enough to ensure that the particles in the oxygen group do not leave the relativistic velocity interval; the most low-energetic particles in the heavier groups, however, do so.

The charge spectrum

Figure 12 shows the charge spectrum at the balloon flight altitude. The spectrum includes all particles accepted, both the relativistic particles which are identified with the MTW $-Z$ relation in Figure 11 and the non-relativistic particles which are identified from measurements of MTW and ΔMTW/ΔR. In all, 61 particles heavier than oxygen are included. The oxygen group (32 particles) has been measured for calibration purposes. The number of oxygen tracks corresponding to the numbers of heavy tracks is about 2.5 times as large as the measured number.

Our condition for the acceptance of a track required that the error in the charge determination should not be larger than 0.2–0.3 units of charge when only purely statistical errors from the measurement of MTW were taken into consideration. The experimental standard deviations in the charge determination have been calculated for the large particle groups in the spectrum. The results are shown in Table 6.

Table 6.

Charge	Standard deviation (units of charge)
8	0.32
10	0.26
12	0.32
14	0.28
24 and 26	0.24

The mean value of the standard deviations is 0.28 units of charge, which is in fairly good agreement with the predictions.

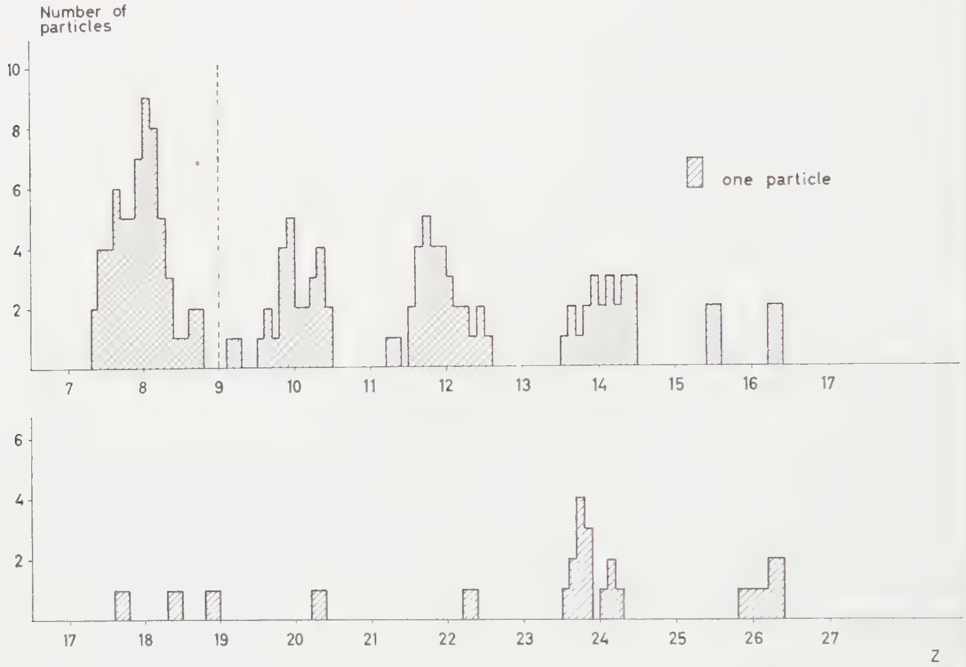

Fig. 12. The heavy part of the heavy primary spectrum at a depth of 18 g/cm² atmosphere and 9 g/cm² emulsion and at a geomagnetic latitude of 41 degrees.

The frequency of wrong identifications

Overlapping distributions.—As was shown in the previous chapter the standard deviation in the charge determination amounts to 0.28 units of charge. If the particles have a Gaussian distribution, a certain but small number of measurements will fall at a distance of more than half a unit of charge from the correct value. If the limit between two charges is put between them, just in the middle, 8 % of the particles will be wrongly identified. That means that out of 61 particles heavier than oxygen on an average 5 will be incorrectly determined. The error in the charge, which amounts to one unit, is however not very serious because most of the wrongly identified particles must fall in tails of comparatively large distributions and can be assigned the correct charge with fairly high certainty in spite of their position in the spectrum.

Non-relativistic particles.—Table 5 shows that $\Delta\mathrm{MTW}/\Delta R$ has been determined for only 70 % of the particles accepted in this paper. The relative amount of non-relativistic particles can be assumed to be the same in the residual 30 % of the tracks as in the above-mentioned 70 %. In this last-mentioned group we have identified 10 non-relativistic particles and in the mean we therefore expect to have a further 4 in the whole material. These 4 particles are identified from their MTW values only, which means that their charges are too high, the errors being 1–4 units of charge.

Deficiency in the identification methods.—As has been stated already a small but non-negligible number of the particles was found to be non-relativistic and identified by measurements of MTW and ΔMTW/ΔR. Identification by this method was found to be possible as soon as the particle momentum is less than some value, $p_1(Z)$. Correct identification by MTW measurements only is on the other hand possible as soon as the momentum is larger than a value $p_2(Z)$. How $p_1(Z)$ and $p_2(Z)$ depend on the charge can be seen in the Table 7 [39]. In the interval lying between $p_1(Z)$ and $p_2(Z)$ none of the methods can give a correct result, the error being one unit of charge. The number of particles in the interval has to be calculated in order to get information of the seriousness of this deficiency in the identification method.

Table 7.

Charge	$p_1(Z)$ GeV/c per nucleon	$p_2(Z)$ GeV/c per nucleon
8	0.9	1.4
12	1.2	1.7
20	1.4	1.9
26	1.5	2.0

The integral energy spectrum of the primary particles can be represented by

$$I_Z(E > E_0) = \frac{K(Z)}{(1+E_0)^\gamma}$$

where $I_Z(E > E_0)$ is equal to the total number of particles of charge Z and with the kinetic energy E exceeding E_0. E and E_0 are expressed in GeV per nucleon. $K(Z)$ does not depend on the energy and γ is a constant which seems to be independent of both energy and kind of particle. According to Jain, Lohrmann, and Teucher [40] a value $\gamma = 1.5$ fits the energy spectrum of the heavy primary particles rather well.

The energy spectrum of the primaries at the flight latitude can be divided into three parts

$$I_Z(E > E_0) = I_Z(E_0 < E < E_1) + I_Z(E_1 < E < E_2) + I_Z(E > E_2).$$

The first term to the right represents the part of the spectrum which can be identified by measurements of MTW and ΔMTW/ΔR. E_0 is the minimum energy allowed for a particle on account of the earth's magnetic field. The second term represents the particles which cannot be identified correctly. E_1 and E_2 are the energy limits for this region. The last term represents the relativistic particles identified by MTW measurements.

In Figure 13 the geomagnetic cut-off momentum has been plotted as a function of the geomagnetic latitude for five particle directions. The curves are based on Vallarta's calculations of the cut-off energy for protons [41]. The two momenta p_1 and p_2 in the figure show the limits between which particles are wrongly identified. It must be pointed out that p_1 and p_2 are larger than $p_1(Z)$ and $p_2(Z)$, the difference being equal to the momentum loss by ionization in the passage from the top of the atmosphere to the point of measurement in the emulsion stack.

As can be seen in Figure 13 the number of wrongly identified magnesium nuclei

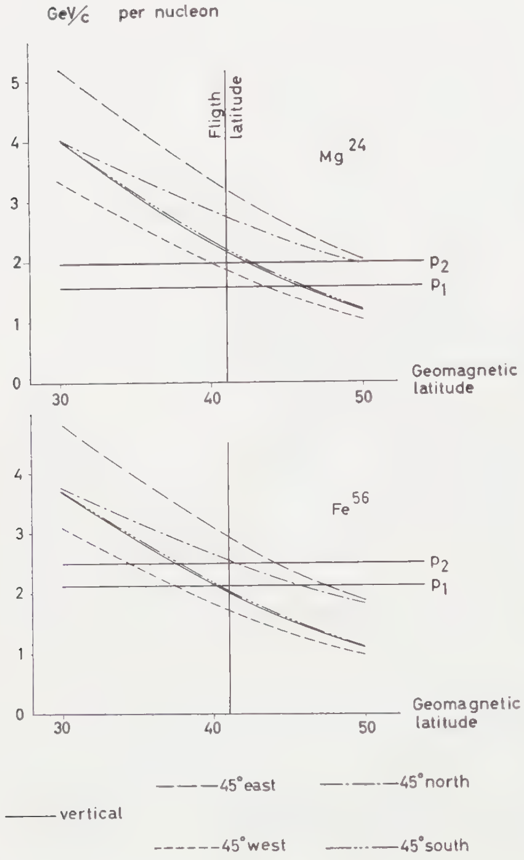

Fig. 13. Cut-off momentum in GeV/c per nucleon as a function of geomagnetic latitude. The momenta p_1 and p_2 are the limits between which it is impossible to identify correctly a heavy primary particle solely from MTW measurements.

must be negligible. Only a small fraction of the particles which come from the west have their momenta in the interval (p_1, p_2).

The interval (p_1, p_2) is more serious for particles in the iron group. We have made a rough estimate of the number of wrongly identified particles in the following way. The stereo angle in which particles are accepted is divided into five parts. One of them is symmetrical around the zenith direction. The remaining four form together a ringshaped stereo angle around the first one. The ring is divided into equal parts directed towards north, south, east, and west and with 45° zenith angle. The stereo angle with the vertical axis has been chosen twice as large as the others. The total flux reaching the stack can be written as a sum of the fluxes from the five directions

$$I(Z) = c(Z) \sum_{i=5} \frac{\Delta\,\Omega_i}{(1+E_{0i})^{\gamma}}$$

where $I(Z)$ is the flux of particles of charge Z, $c(Z)$ is a constant, $\Delta\Omega_i$ is the stereo angle in the direction i, and E_{0i} is the cut-off energy in the same direction.

The number of particles in the interval (p_1, p_2) is equal to

$$I[Z, (p_1, p_2)] = c(Z) \sum_{i=5} \left(\frac{\Delta \Omega_i}{(1+E_1)^{1.5}} - \frac{\Delta \Omega_i}{(1+E_2)^{1.5}} \right)$$

where the sum is taken over such directions that $E_{0i} < E_1$. If $E_{0i} > E_1$, we have substituted E_1 by E_{0i} in the formula.

If the values in Figure 13 are used for the cut-off energy, calculations show that about 11 per cent of the particles in the chromium and iron groups fall within the interval (p_1, p_2) and are wrongly identified.

The conclusion of the discussion is that the spectrum of 61 particles heavier than oxygen does not contain more than 1–2 particles in the interval of wrong identifications.

There are some observations which indicate that the geomagnetic latitude 41°, which is derived from conventional geomagnetic coordinates, is lower than the cosmic ray geomagnetic latitude, the difference being approximately 4° [42]. This change in geomagnetic latitude will slightly increase the number of wrongly identified particles but the number is still too low to disturb the spectrum.

The whole discussion of the errors has shown that there may be about 10 particles which are wrongly identified. That is however a comparatively small fraction of the total number of particles and they will not have any serious influence on the conclusions which can be drawn from the spectrum.

Relative abundance of heavy and very heavy elements

The heavy part of the primary spectrum is sometimes divided into two parts, a heavy group (H') and a very heavy group (VH). The boundary between the groups has been chosen in a different manner in different papers, from $Z = 15$ in a paper by Bisi *et al.* [31] to $Z = 20$ in a paper by Rajopadhye and Waddington [24]. There is no clear and natural division of the spectrum but a study of Figure 12 shows that it is convenient to put the limit between $Z = 16$ and 17 in order to have the four frequently occurring elements Ne, Mg, Si, and S in the same group, and the rest of the spectrum in the other.

The frequency of particles in the two groups must be extrapolated from the point of measurement to the top of the atmosphere to obtain the true primary flux ratio. The extrapolation in the air is made by solving the one-dimensional diffusion equations for heavy particles traversing the atmosphere [11]. The solutions of these equations are

$$N_{VH}(x) = N_{VH}(0) \cdot e^{-x/\lambda_{VH}^{a'}}$$

$$N_{H'}(x) = N_{H'}(0) \cdot e^{-x/\lambda_{H'}^{a'}} + \frac{\lambda_{VH}^{a'} \cdot \lambda_{H'}^{a'}}{\lambda_{H'}^{a'} - \lambda_{VH}^{a'}} \cdot \frac{P_{VH,\,H'}^{a}}{\lambda_{VH}^{a}} \left[N_{VH}(0) \cdot e^{-x/\lambda_{H'}^{a'}} - N_{VH}(x) \right]$$

$$\lambda_{VH}^{a'} = \frac{\lambda_{VH}^{a}}{1 - P_{VH,\,VH}^{a}}; \quad \lambda_{H'}^{a'} = \frac{\lambda_{H'}^{a}}{1 - P_{H',\,H'}^{a}}.$$

$N_{VH}(x)$ and $N_{H'}(x)$ are the number of very heavy and heavy particles at depth x in the atmosphere. λ^a_{VH} and $\lambda^a_{H'}$ are the interaction mean free paths for very heavy and heavy particles in air. $P^a_{VH,\,VH}$, $P^a_{VH,\,H'}$ and $P^a_{H',\,H'}$ are the fragmentation probabilities in air. When flight altitude and angular distribution are taken into consideration we have found that $x = 18$ g/cm².

$N_{VH}(x)$ and $N_{H'}(x)$ are the intensities of the two components at the entrance into the emulsion stack. A particle to be accepted for measurement must further have a minimum track length in the stack; this is determined from the criteria of acceptance discussed in a previous section. The minimum track length is composed of two parts, the first part is equal to the distance from the point of entry into the stack to the point where the measurements start; and the second one is equal to the minimum accepted track length according to Figure 10. The total minimum track length which is called y in the formula below is found on an average to be 9 g/cm².

One of our criteria of acceptance stated that the particles were not allowed to show any nuclear interaction from the point of entry to the end point of the measurements. That means that the number of particles in the heavy particle beam which are accepted for measurements is reduced according to a simple exponential law. Thus after a traversal of y g/cm² emulsion the intensities will be

$$N_{VH}(x+y) = N_{VH}(x) \cdot e^{-y/\lambda^e_{VH}}$$

$$N_{H'}(x+y) = N_{H'}(x) \cdot e^{-y/\lambda^e_{H'}}$$

where λ^e_{VH} and $\lambda^e_{H'}$ are the interaction mean free paths for very heavy and heavy particles in the emulsion.

The interaction mean free paths are determined from the calculations by Cester *et al.* [23]. The fragmentation probabilities in air have been calculated from fragmentation probabilities in emulsion determined by Rajopadhye and Waddington [24] for the very heavy and heavy particles. The transformation from emulsion to air is made by a simple multiplication by a factor 1.4. The figure is obtained as a mean value of ratios of fragmentation probabilities in air and emulsion. The probabilities have been collected from several papers and include all groups of charges in the heavy particle spectrum. We do not believe that this very crude method of obtaining the fragmentation factors will increase the errors to any great extent. The difference in the definition of the VH and H' regions in the paper by Rajopadhye and Waddington as compared to that which we have used is also taken into consideration. The constants are given in Table 8.

Table 8.

λ^a_{VH}	$\lambda^a_{H'}$	λ^e_{VH}	$\lambda^e_{H'}$	$P^a_{VH,\,VH}$	$P^a_{VH,\,H'}$	$P^a_{H',\,H'}$
15 g/cm²	21 g/cm²	28 g/cm²	39 g/cm²	0.34	0.25	0.17

The relative abundance of the two heavy particle groups is shown in Table 9. It also includes a comparison with the Suess and Urey cosmic abundance data [43] which definitely shows that the particles in the VH region are much more frequent in the radiation than in the universe.

Table 9.

	$\frac{N_{VH}}{N_{H'}}$
Depth of measurement	0.36 ± 0.10
Top of atmosphere	0.48 ± 0.14
Suess and Urey	0.07

Abundance ratios in the H' group

At first we will discuss the relative abundance of particles with odd and even charge. In an early investigation by Bradt and Peters [2] it was found that the frequency of the even elements neon, magnesium, and silicon was somewhat larger than the frequency of the odd elements sodium, aluminium, and phosphorus. The number of identified particles was however too low to allow definite conclusions about the relative abundance of odd and even nuclei. Dainton, Fowler, and Kent [6] have later found that the abundance of particles with even charge is approximately three times as large as the abundance of particles with odd charge. In contrast to these results there stand several investigations in which no difference has been found between the relative abundance of odd and even particles.

It seems as if the ratios reported in different papers were dependent on the accuracy with which the charge of a particle was determined. As our measurements have an error in the charge determination which is smaller than the error in most earlier investigations we have found it possible to give more definite figures for the odd-even ratio.

If the separating line between two consecutive charges in the spectrum in Figure 12 is put half-way between them, the number of different charges will be the one reported in Table 10. Particles with the charge in the interval $8.5 < Z < 9.0$ are not included in the fluorine group as most of them must belong to the tail of the oxygen distribution.

Table 10.

Element	F	Ne	Na	Mg	Al	Si	P	S
Number of particles	1	13	1	14.5	0.5	11	1	3

The ratio between the numbers of odd and even particles is found to be equal to 0.08 ± 0.05. The ratio is small but in spite of that it must be an upper limit because some of the particles in the odd groups are found in the tails of even particle distributions and may have been wrongly identified.

The low ratio seems to have both astrophysical and nuclear physical reasons. Part of the nuclei reaching the atmosphere are true primaries, i.e., they have not been changed by collisions on the way from the cosmic ray source, whereas another part consists of fragmentation products from collisions between primary nuclei and interstellar matter. According to the tables of Suess and Urey [43] the universal abundance of the elements fluorine to sulfur shows a very pronounced predominance of nuclei with even charge. That means that among the really primary nuclei particles with even charge dominate considerably. Even if the composition of the cosmic ray source is not exactly the same as the mean universal composition there is no reason to assume any change in the odd-even ratio large enough to have influence on the spectrum.

The generation of new nuclei by primary particle collisions with interstellar matter will also give more particles with even charge than with odd. In the first approximation it can be assumed that in a spallation reaction the probability of producing new elements is a smooth function of the number of nucleons in the product nucleus [44]. That means that the ratio between odd and even charges will be approximately equal to the ratio between the number of stable isotopes of the odd and even elements. This ratio is about 1:3 in the region, and we can thus expect the same ratio between odd and even particles of non-primary origin in the radiation. Gottstein [9] and also Cester *et al.* [23] have found a predominance of evenly charged fragments in collisions between heavy primaries and the nuclei in the emulsion. If the same predominance exists in collisions between the primary particles and the interstellar matter the ratio between odd and even collision products will be still less than 1:3.

Three elements, neon, magnesium, and silicon are found in approximately the same amounts in the radiation. A comparison between the relative abundance in the radiation and the mean universal composition as given by Suess and Urey shows a remarkable difference for neon, which is much more abundant in the universe than in the radiation. The data are collected in Table 11. The cosmic radiation ratios given in the table are valid at the depth of measurement. At the top of the atmosphere the abundance figures for Ne and Mg must be somewhat smaller on account of differences in the production probabilities by fragmentation and also of differences in their mean free paths. The figures may either reflect a feature in the composition of the cosmic ray source or depend on the high ionization potential for neon as compared to the other two elements which may reduce the probability for a neon nucleus to be accelerated.

Table 11.

	Ne	Mg	Si
Cosmic radiation	1.2	1.3	1.0
Suess and Urey	8.6	0.9	1.0

Abundance ratios in the *VH* group

The frequency of particles in the region $17 \leqslant Z \leqslant 23$ is low. The number of particles in the interval in our spectrum is not larger than the expected number of fragments produced in collisions between the heaviest elements and air nuclei above the stack. That means that there may not necessarily be any primaries in the interval. Bisi *et al.* [31] have found a group of Ca nuclei nearly as large as the Si-group. Nothing in our spectrum supports this result but it must be pointed out that our material is rather small and that there may exist a small Ca-group.

We have found two fairly abundant particle groups which have been identified as chromium and iron. The statistics are very poor but large enough to show that chromium and iron nuclei have approximately the same frequency in the primary radiation.

We have found no particles heavier than iron.

Relative abundance of O, Si, and Fe

If the heavy primary spectrum is divided into three groups, Li—O, F—Si, and P—Fe, the last element in each group is appreciably more abundant than any heavier element. Thus the number of fragments with charges 8, 14, and 26, produced in collisions between heavier particles and the matter traversed, will be low in comparison to the number of primary oxygen, silicon, and iron nuclei, if the amount of matter passed does not exceed a few mean free paths. That means that the relative abundance of these three elements is less disturbed than of most other combinations of elements in the spectrum.

The second column in Table 12 shows the abundance of nuclei after the traversal of 18 g/cm^2 air and 9 g/cm^2 emulsion (depth of measurement). The figures for Fe and Si are taken directly from the spectrum. The oxygen abundance is calculated from the knowledge of the size of the M group (C, N, O) relative to the H group (F—Fe) [25] and of the relative frequency of the elements in the M group as shown in paper 1.

Table 12.

Element	Abundance at the depth of measurement	Abundance at the top of the atmosphere	Abundance at the cosmic ray source	Universal abundance Suess and Urey
O	82	203	313	313
Si	11	35	67	15
Fe	4	20	55	9

The third column shows the abundance at the top of the atmosphere. The mean free paths used in the extrapolation are calculated from λ values given by Cester *et al.* [23]. In the fourth column we have tried to estimate the frequency of the three elements at the source of the cosmic radiation. We have assumed that the amount of interstellar matter traversed is equal to one mean free path for iron. This is approximately in accordance with a calculation made by Koshiba, Schultz, and Schein [22] based on the contents of Li, Be, and B in the radiation and also with measurements of the intensity of the same elements by Appa Rao *et al.* [25]. The cross section is taken proportional to $A^{2/3}$, where A is the atomic weight.

The last column in Table 12 shows the mean universal abundance of oxygen, silicon, and iron as given by Suess and Urey [43]. A comparison with the cosmic ray figures shows that relative to oxygen the heavier elements, silicon and iron, have a much higher abundance in the radiation than in the universe. There are a few objections to the direct comparison, and this may to some extent explain the difference in the relative abundance of the elements. First of all the statistical weight of the iron group is very low; it may very well be in error by a factor of two. The ionization potentials of the three elements are slightly different, $I(\mathrm{O}) = 13.6$ eV, $I(\mathrm{Si}) = 8.1$ eV, and $I(\mathrm{Fe}) = 7.9$ eV. Silicon and iron are consequently more easily ionized than oxygen which may favour their injection into the cosmic ray accelerator. At low energies, when the nuclei are not completely stripped, Z_{eff}/A is less for iron and silicon than for oxygen [45]. That means that iron and silicon diffuse faster than oxygen out of the source region, if it is located in a magnetic field whose gradient differs from zero. This may under special conditions give rise to an excess of iron and silicon relative to oxygen.

Even if these sources of error are taken into consideration we find it very difficult to assume that the cosmic ray source does not contain an appreciable excess of silicon and iron relative to oxygen, if the comparison is made with the mean universal composition.

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